Planetary Systems in the Universe - Observation, Formation and Evolution
Proceedings IAU Symposium No. 202, ©2004 IAU
Alan Penny, Pawel Artymowicz, Anne-Marie Lagrange, & Sara Russell, eds.

Toward Consistent Models of Protoplanetary Discs

Mauricio Reyes-Ruiz

Instituto de Astronomía, UNAM, Apdo.Postal 877, 22800 Ensenada, B.C., México

Abstract. In this paper we present results on the effect of the vertical stratification of magnetic diffusivity, expected in current models of protoplanetary discs, on the development of the magnetorotational instability. Specifically, on the basis of a quasi-global, linear analysis we study the operation of the magnetorotational instability across the so-called dead zone of protoplanetary discs. Our results indicate that the predicted strong vertical diffusivity gradients can damp the instability in such regions. This suggests the necessity of a revision of current models for the structure and evolution of protoplanetary discs.

1. Introduction

Understanding the initial stages of the process of planet formation requires reliable, detailed models for the structure and evolution of protoplanetary discs. Currently, most models are based on the formalism of viscous accretion disks, in which a turbulent origin for the "viscous" stresses driving the evolution of the disc, is presumed. In the last ten years, the magnetorotational instability (MRI) has been identified as a possible source for the presumed turbulence in thin accretion discs (see Balbus & Hawley 1998 for a review of the topic).

As found by Jin (1996) the MRI will arise at a given radius in a disc, leading to self-sustained turbulence and viscosity, if the diffusive timescale is longer than the Alfven wave crossing time for all modes of the MRI in the linear regime. As pointed out by several authors (see D'alessio et al. 1998 and references therein) in most models of protoplanetary discs the ionization degree, and consequent ohmic magnetic diffusivity, varies significantly over the disc. Inwards of ~ 1 AU, the temperatures are high enough so that thermal ionization allows the development of the MRI. In an intermediate region, out to ~ 10 AU, only thin layers near the surface of the disc are sufficiently ionized due to the incidence of energetic particles of galactic or stellar origin.

With these results, and the assumption that the MRI is the only possible source of turbulence in protoplanetary discs, Gammie (1996) proposed a modification to standard, 1-D (radial) models as those of Ruden & Pollack (1991). In Gammie's models, at intermediate distance from the central object, the transport of angular momentum and mass through the disc takes place only in active layers near the surface, while a broad region around the disc midplane remains dormant accumulating material. These layered accretion models have been further studied in a time dependent version by Stepinski (1999) and Armitage (these proceedings) with results suggesting that the peculiar properties around

https://doi.org/10.1017/S0074180900218251 Published online by Cambridge University Press

the so-called "dead" zone can have important consequences on the process of planet formation.

In this work we present a revision of the instability criterion leading to the suggestion that layered accretion takes place in protoplanetary discs. A quasi-global, linear analysis of the MRI in regions of strong diffusivity gradient, as expected across the dead zone, is carried out. The methodology for the analysis presented in this paper and additional results are described in detail in Reyes-Ruiz (2001).

2. Results

Our aim is to study the MRI in the middle, poorly ionized portions of protoplanetary discs, concentrating on the effect of magnetic diffusivity stratification in the vertical direction. We adopt boundary conditions corresponding to a hot, tenuous halo model for the exterior of the disk. Growth rates and eigenmodes for the MRI are computed for weak unperturbed magnetic fields, $\beta \leq 0.1$, where β is the square of the ratio of the Alfven wave speed and the sound speed at the disc midplane. We also concentrate on moderately diffusive disks, a condition written as $1 < R_m \leq 10^3$, where the parameter R_m can be seen as the ratio of the characteristic diffusive timescale over a length H, the disc half-thickness, to the dynamical timescale.

As pointed out by Dolginov & Stepinski (1994) a strong vertical gradient in the ionization degree is set up due to shielding of energetic particles by disc material. At a given radius, the magnetic diffusivity increases almost exponentially with a characteristic scale, l_o, dependent on the surface density. The precise values of l_o and R_m depend on the protoplanetary disc model. The other parameter affecting the development of the MRI, β, is determined by the assumed unperturbed magnetic field probably related to conditions external to the disc.

In Figure 1 we summarize our results by comparing the predicted properties of standard, viscous accretion disc models for protoplanetary discs with the necessary conditions for the MRI to arise. Depending on the value of β_c, marked radii allow us to determine in what regions of the disk the MRI will develop. For example, for the disk model with $\alpha = 10^{-2}$ and $\dot{M} = 10^{-8} M_{\odot}$/yr (short dashed line), even if the seed field is as strong as $\beta = 10^{-2}$, in a broad region between several AU and the outer boundary if the inner well ionized region, $R_{\rm IAR}$ (square), located at less than 0.3 AU for this model, the MRI will not arise. For the same model, if $\beta = 10^{-4}$, outwards of $R_{\rm IAR}$ the whole disk will be stable. A similar analysis can be performed for the reader's preferred specific model.

3. Conclusions

We have found that the expected stratification of the magnetic diffusivity in standard protoplanetary disc models affects significantly the development of the MRI. In broad regions, typically extending from $\sim$ 1 AU to tens of AU, the instability is damped. If the MRI is the only source of turbulence and anomalous viscosity in protoplanetary discs, our results suggest the necessity of a major revision of current protoplanetary disc models.

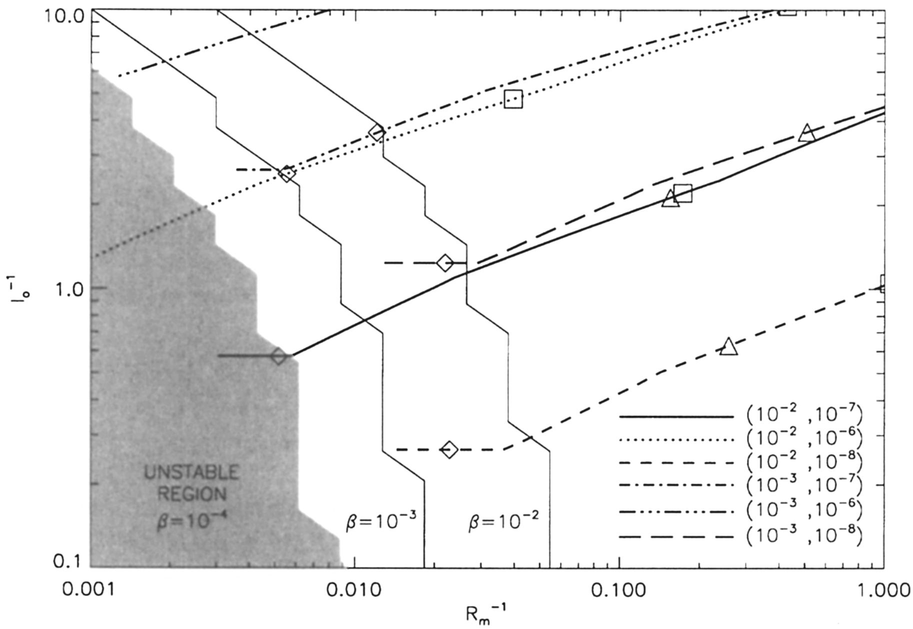

Figure 1. Comparison of R_m and l_o^{-1} values for various PP disc models with the stability conditions resulting from our analysis. In the legend of linestyles the first number indicates the value the α parameter and the second the mass accretion rate in solar masses per year.. The leftmost edge of such lines correspond to the value of R_m^{-1} and l_o^{-1} at 60 AU. Over each line the square marks the $R_{\rm IAR}$ and the triangle and diamond mark where $R = 1$ and $R = 10$ AU respectively.

References

Balbus, S.A,. & Hawley, J.F. 1998, Rev. Modern Physics, 70, 1

D'alessio, P., Canto, J., Calvet, N., & Lizano, S. 1998, ApJ, 500, 411

Dolginov, A., & Stepinski, T.F. 1994, ApJ, 427, 377

Gammie, C.F. 1996, ApJ, 457, 355

Jin, L. 1996, ApJ, 457, 798

Reyes-Ruiz, M. 2001, ApJ, 547, 465

Ruden, S.P., & Pollack, J.B. 1991, ApJ, 375, 740

Stepinski, T.F. 1999, in Proceedings of the 30th Annual Lunar and Planetary Science Conference, abstract no. 1205